2003 Diesel Engine Emissions Reduction Conference
Newport, Rhode Island
24-28 August 2003

Catalytica ENERGY SYSTEMS

Use of a Diesel Fuel Processor for Rapid and Efficient Regeneration of Single Leg NOx Adsorber Systems

R. Dalla Betta, J. Cizeron, D. Sheridan, T. Davis
Catalytica Energy Systems Inc.
Mountain View, California

DEDICATED TO INNOVATIVE SOLUTIONS FOR CLEAN ENERGY PRODUCTION

Outline

- Overview-Requirements of a NOx adsorber system
  - Why a diesel fuel processor?
    - Regeneration
    - Desulfation
- Diesel Fuel Processor (DFP) performance requirements
- Engine test data
  - Fuel processor performance
  - Fuel penalty
  - Early DFP-NOx adsorber performance
- Desulfation strategy
- Conclusions

NOx Adsorber Overview

- Typical system characteristics
  - > 90% NOx emissions control demonstrated
  - Typically 2 to 4 liters adsorber volume per liter engine displacement
  - Regeneration and conversion of NOx to N_2 requires reducing environment
  - Reactive reductants allow operation at lower exhaust temperatures
  - ULSD compatible with periodic desulfation
- Issues related to adsorber performance
  - Adsorber must be fully regenerated with each cycle
  - Regeneration difficult at low temperatures
  - Desulfation requires high temperature
  - Adsorber durability appears to be a problem

NOx Adsorber Regeneration

- Requirements
  - Exhaust must be reducing
    - 0% O_2 and some reductant level
  - Desire regeneration capability over entire engine operating range
- Issues
  - Effective NOx regeneration difficult below 300°C with in-pipe diesel injection
  - Post cycle in-cylinder injection can generate more reactive reductants but can impact engine durability
  - Ideal route to "rich" exhaust not established
    - Engine operation at rich conditions not acceptable
    - Late cycle injection or in pipe injection requires combustion on DOC or NOx adsorber
    - Reaction of excess oxygen + fuel on adsorber can generate local high temperatures

NOx Adsorber Operation

NOx Adsorber reactions

- Lean NOx trapping reaction

  (typical component is $BaO/BaCO_3$)

$$BaO + NOx \xrightarrow{CAT} Ba(NO_3)_2$$

- Regeneration cycle

Exhaust must become reducing

$$Ba(NO_3)_2 + [red] \xrightarrow{CAT} BaO + NO_2$$

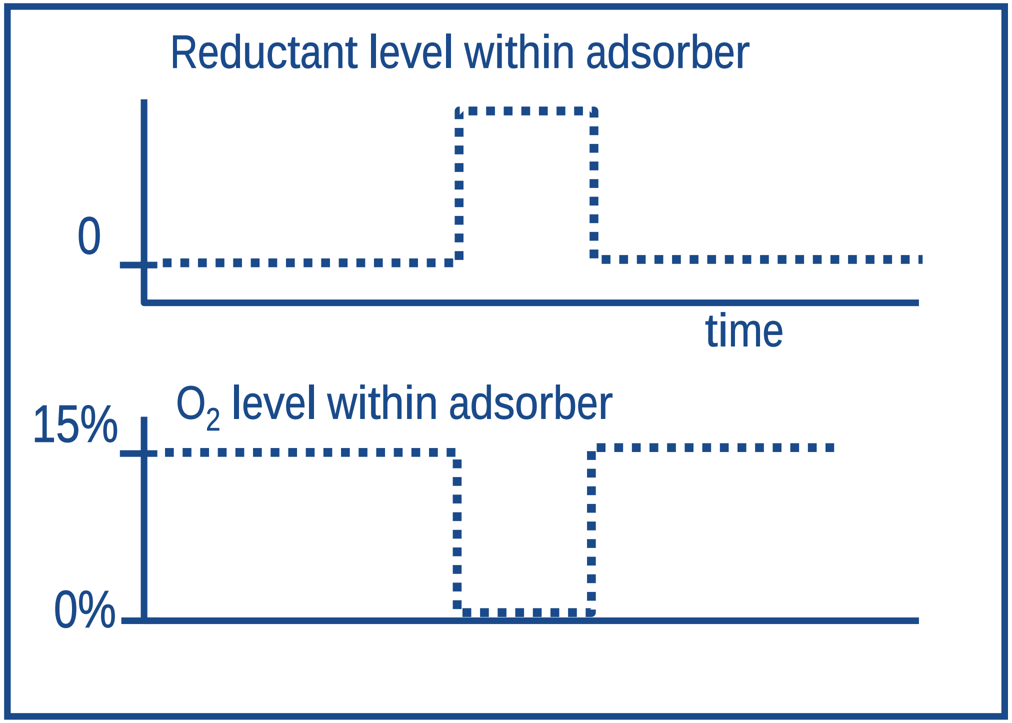
$$NO_2 + [red] \xrightarrow{CAT} N_2 + H_2O/CO_2$$

[red] = reducing agent, e.g. H_2 or CO

Regeneration cycle

$$CH_{1.8} + O_2 \xrightarrow{CAT} CO_2 + H_2O$$

$$CH_{1.8} + H_2O \xrightarrow{CAT} CO + H_2$$



NOx Adsorber Desulfation

- Fuel sulfur poisons NOx adsorption capacity
  - Desulfation frequency depends on fuel sulfur level and NOx adsorber size (capacity)
- Desulfation requirements
  - NOx adsorber must be heated to 600 to 750°C
  - Reducing environment removes sulfur
- Impact on adsorber durability
  - Desulfation appears to be the primary driver of degradation
  - Potential causes of degradation
    - High temperature during desulfation cycle
    - Local hot spots arising from diesel fuel combustion on the adsorber catalyst

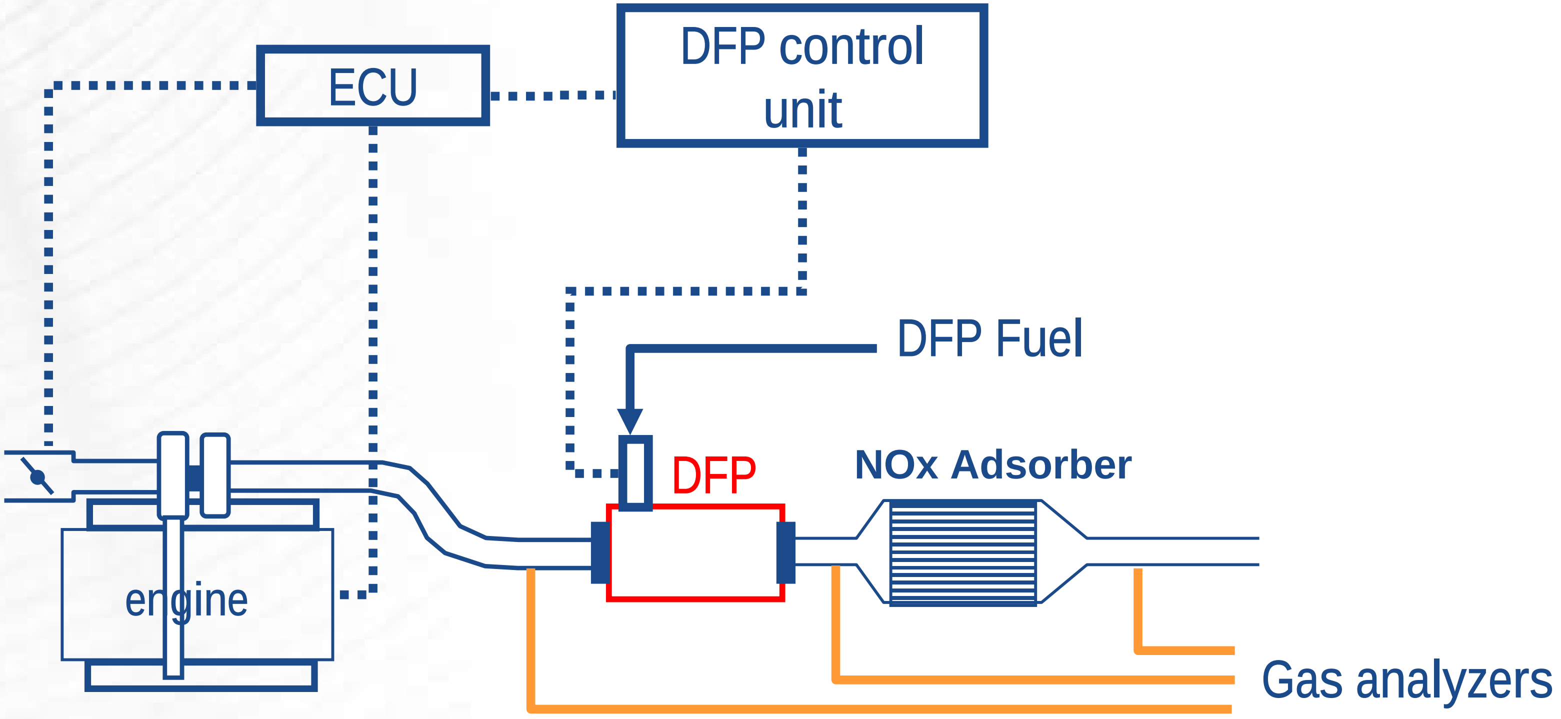
Diesel Fuel Processor (DFP)

Target Performance Requirements

- Diesel fuel only required input
- Volume < 1 liter per liter engine displacement
- NOx adsorber regeneration
  - Convert diesel fuel efficiently to effective reducing agents, preferably H_2 and CO
  - Operate over full engine operating range
  - Rapid regeneration of NOx adsorber with minimal fuel penalty
- NOx adsorber desulfation
  - Allow rapid desulfation at lowest temperature possible
    - Combust fuel to "gently" heat the NOx adsorber to 500-750°C
    - Provide H_2/CO reductant to effect desulfation at lower temperatures
- Provide exhaust heat to aid in PM filter regeneration

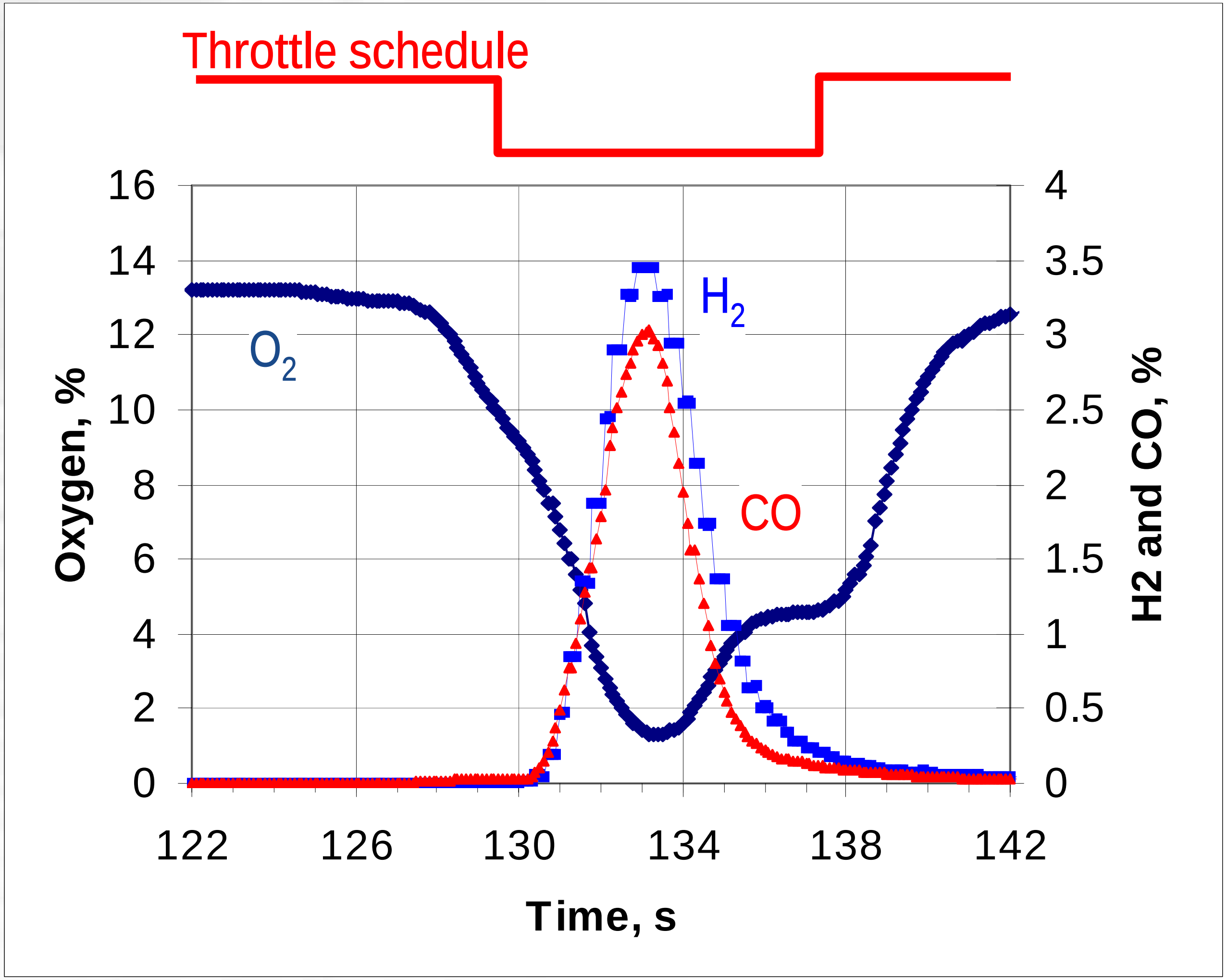
DFP Dynamometer Engine Testing

- 7-9 liter engine, ~ 3 to 4 g/kW-hr NOx emissions level
- Single leg system with DFP followed by “black box” NOx adsorber
- DFP sized to ~0.9 liter per liter engine displacement
- Intake air throttle to control exhaust O_2
- DFP integrated with ECU to control regeneration cycle



DFP NOx Adsorber Regeneration Cycle

50% load point

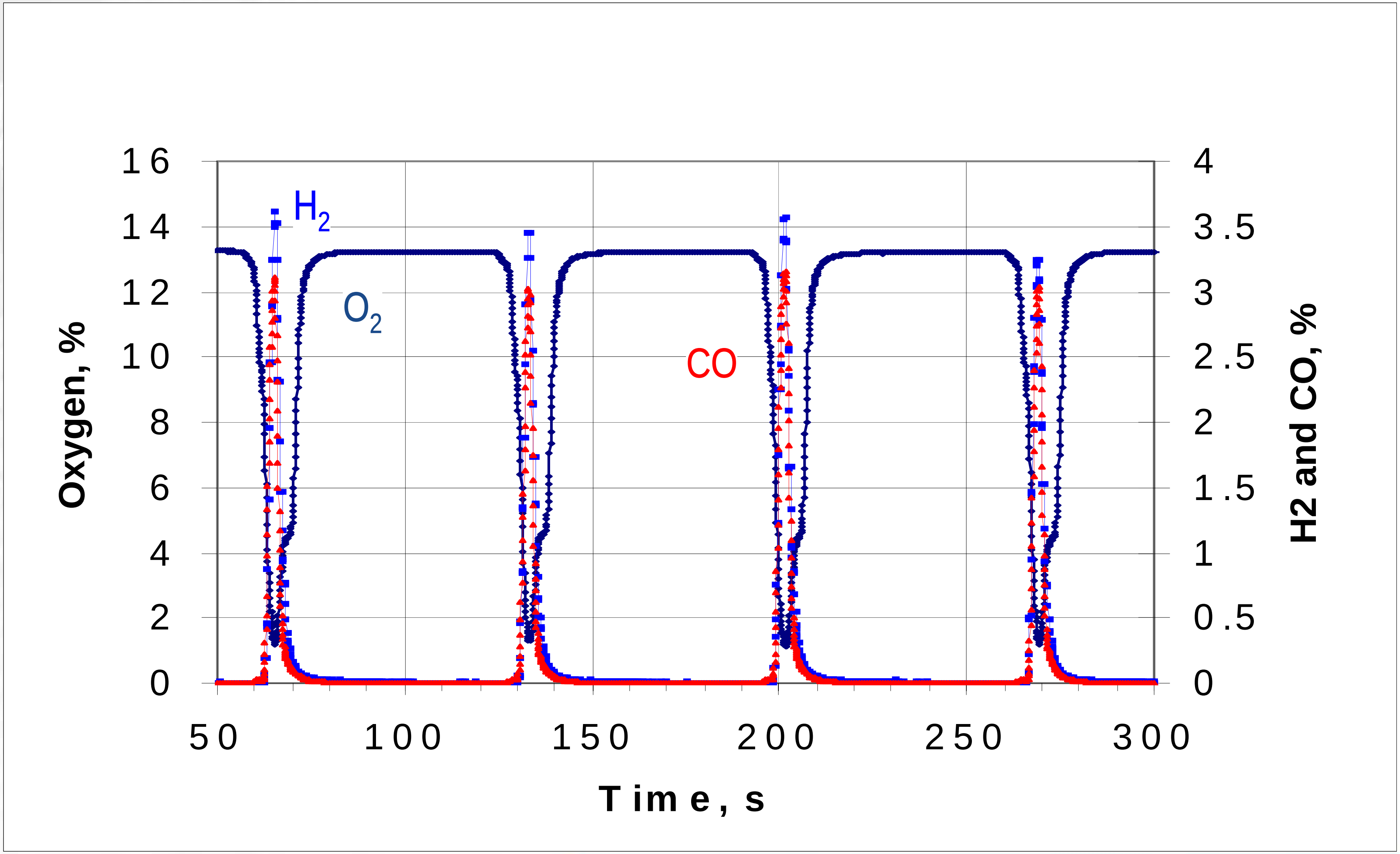


- Engine throttled to ~5% O_2
- 3 second rich regeneration cycle

Lean-Rich NOx Adsorber Cycle

Typical engine cycle

- 60 s lean with 3 second rich regeneration



DFP Performance Summary

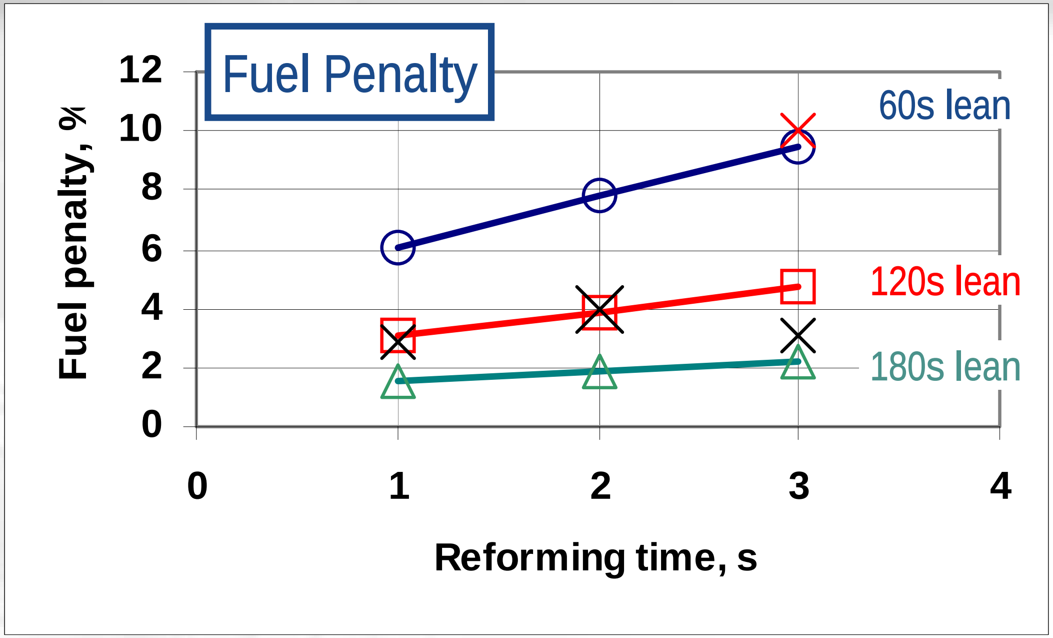
- Fuel required by DFP can be divided into 3 categories

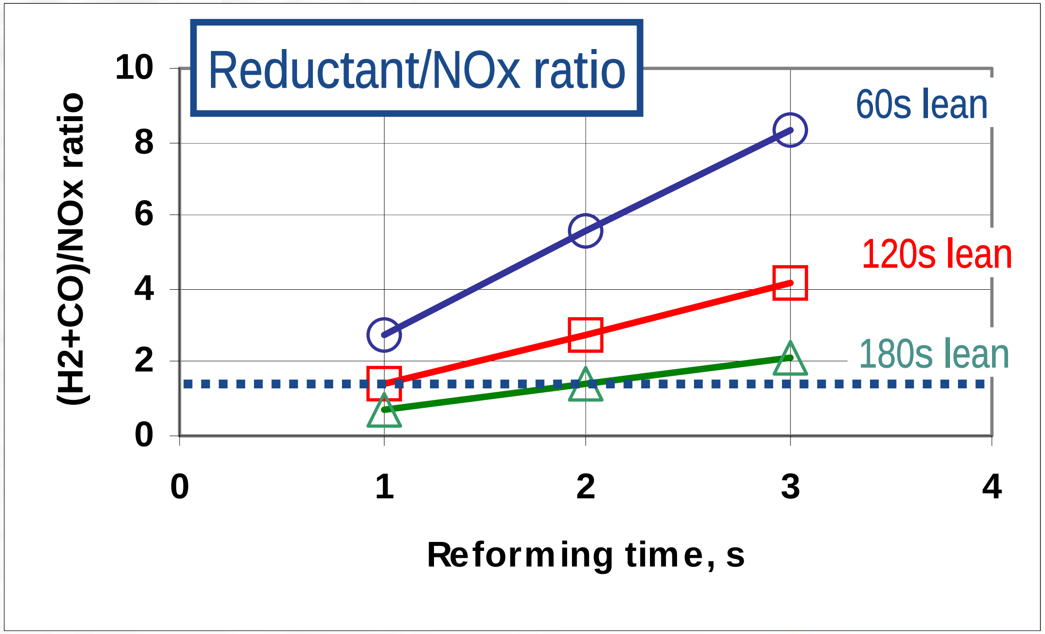
DFP Regeneration cycle

- Additional fuel due to throttled engine
- Fuel to reduce exhaust O_2 to zero
- Fuel to generate H_2/CO

- Optimization to minimize fuel penalty
  - Engine throttling is an effective way to reduce exhaust O_2
    - 5 to 8% O_2 may be effective lower limit for some engine operating regions
  - Fuel combustion to remove exhaust O_2 is required in any regeneration strategy
  - Effective conversion of fuel to H_2 and CO
  - High utilization of H_2 and CO to regenerate NOx adsorber

DFP Cycle Optimization





<u>Fuel penalty: 50% load</u>

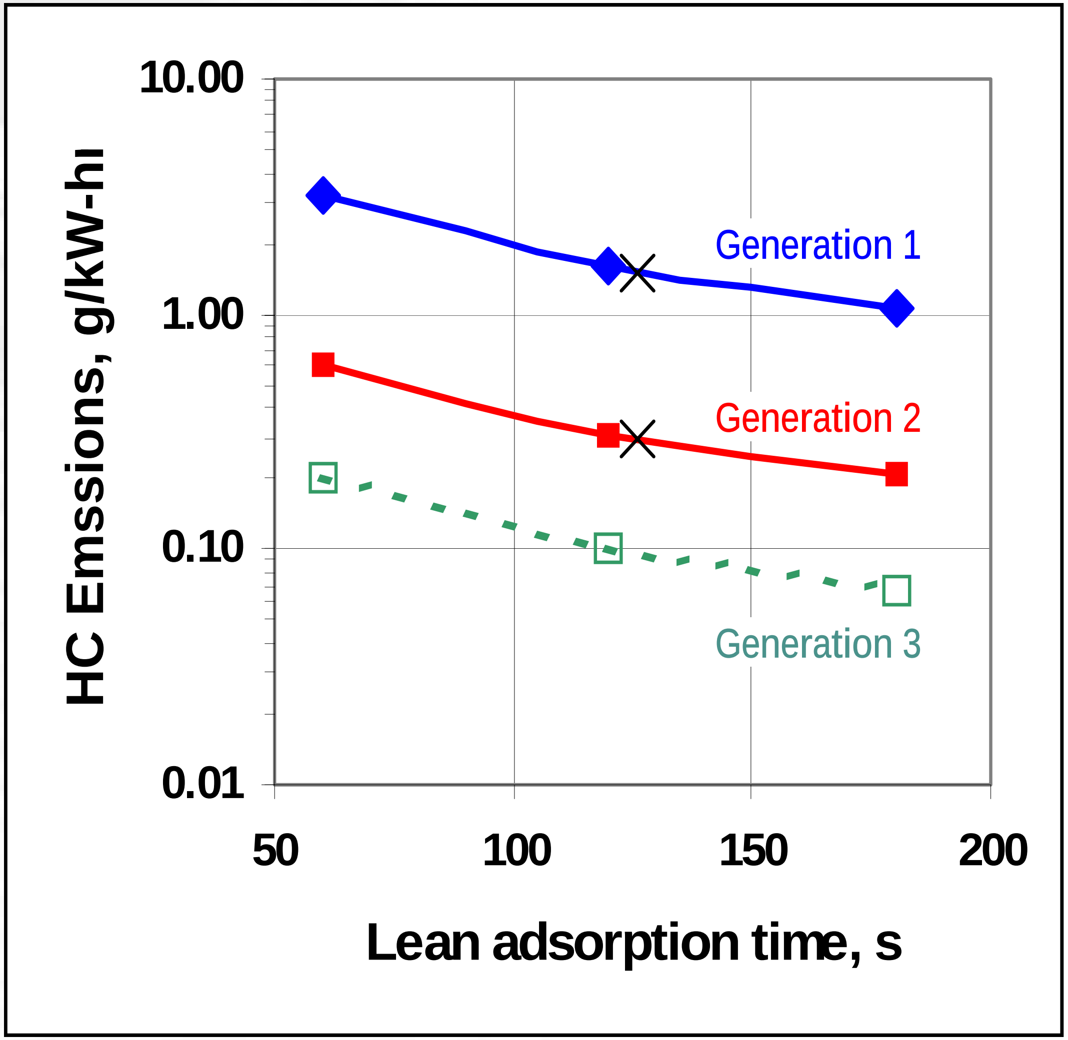
- Theoretical estimate of DFP fuel penalty agrees closely with engine results
- X points are engine test data

<u>Implications:</u>

- Fuel penalty reduced by:
  - Shorter reforming time
  - Longer lean trapping time
- DFP cycle produces large excess of reductant (H_2+CO) compared to NOx trapped

Diesel Fuel Breakthrough

- 50% load data (X) and simulation



Hydrocarbon emissions

- Measured for several different DFP designs
- Generation 3 currently under development (initial results)
- In later designs, larger portion of HC emissions is methane
- Longer lean adsorption time reduces HC emissions

Early DFP-NOx Adsorber Results

- DFP + NOx adsorber system performance

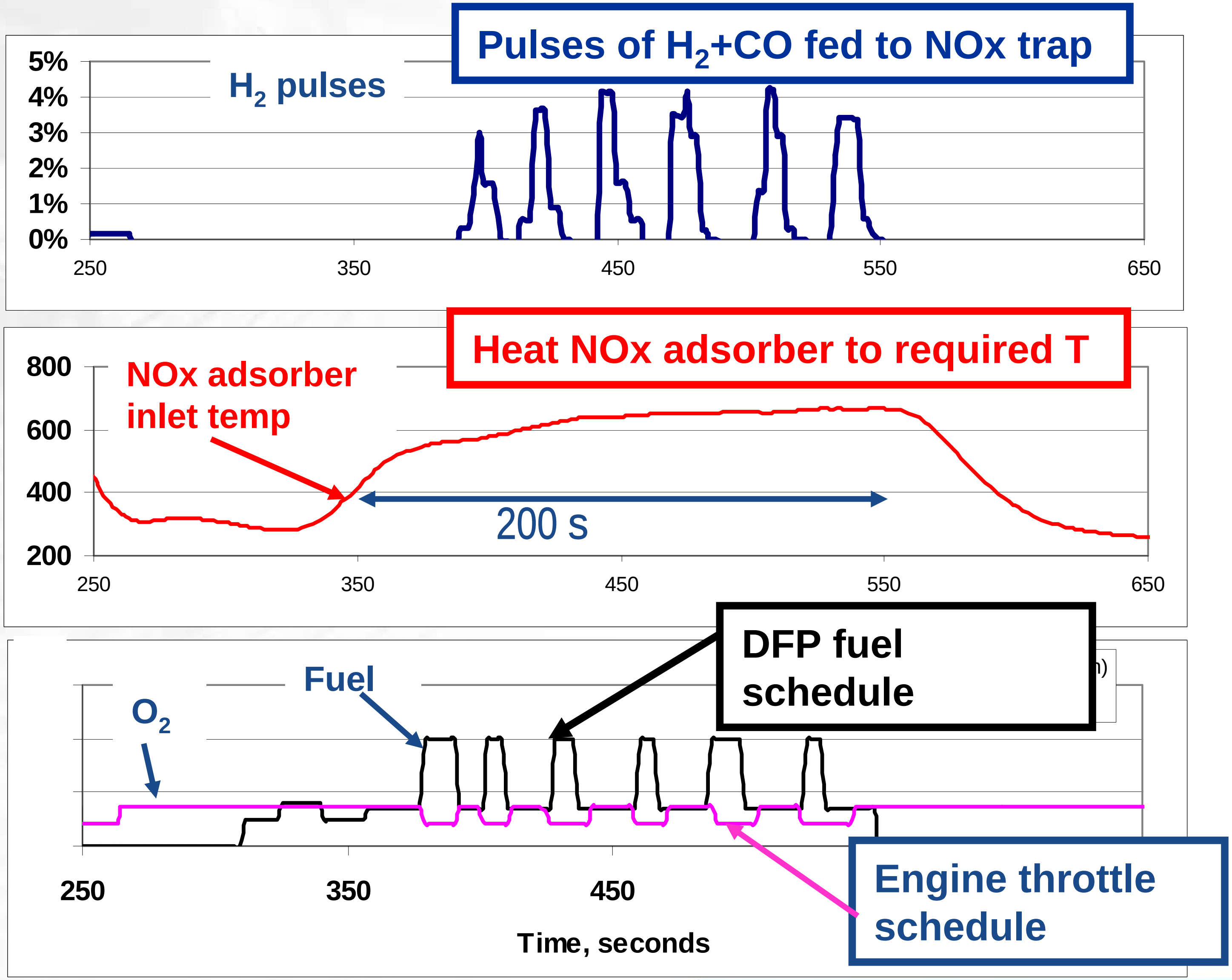
Lean time	Rich time	Fuel penalty	NOx conversion
s	s	%	%
60	2	7.3	>95
120	3	4.5	~92
120	2	3.8	~87

- Best performance would require a NOx adsorber optimized for combination with DFP
  - Designed to effectively utilize H_2/CO reductant
  - High NOx capacity desirable
    - Trade off with cost and vehicle packaging

Desulfation Simulation—Rig results

Simulated exhaust

- **500 SLPM, 250°C**
- **8% CO_2, 12% O_2, 8% H_2O, 1ppm SO_2**



Desulfation cycle

- Heat adsorber to 500 to 600°C
- Provide reactive reductant as needed

Summary/Conclusions

- A diesel fuel processor could provide substantial advantage in the regeneration and optimization of single leg NOx adsorber system
- NOx adsorber regeneration
  - Demonstrated operation at 180°C exhaust temperature
  - Further development and integration with engine operation should allow operation over entire engine operation
- Desulfation
  - Could lower desulfation temperature and time and increase NOx adsorber durability
- Could be used to enhance PM filter regeneration
  - Increase exhaust temperature to PM filter